Modeling and Simulation of Novel Structure for Sub-millimeter Solid-state Accelerometer with Piezoresistive Sensing Elements

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ABSTRACT

This paper presents the modeling and simulation of new structure for solid-state three degrees of freedom (3-DOF) micro accelerometer utilizing piezoresistive effect in single crystal Si. The proposed sensor can detect three components of linear acceleration simultaneously. The sensing structure consists of combined cross-beam and surrounding beams and seismic mass. Therefore, this novel proposed sensor is showing good performance than other miniaturized sensor structures reported thus far.

Keywords: accelerometer, piezoresistor

1 INTRODUCTION

MEMS (Micro Electromechanical Systems) based accelerometer is one of the most important types of the mechanical silicon sensors, since there have been large demands for accelerometers in automotive applications, where they are used for crash detection, and for vehicle stability systems. In addition, due to small size and light weight, they are also used in biomedical and robotics applications for active motion monitoring, and in consumer for stabilization of pictures in camera, head-mounted displays. A substantial study on micromachined accelerometers has been reported so far, with the working principles are mainly based on the piezoresistive effect, capacitance, tunneling effect, resonant, and so on [1]. Among those, the piezoresistive accelerometers have many advantages such as the simplicity of the structure and batch-fabrication process, as well as the readout circuitry, since the resistive bridge (Wheatstone bridge) has low output-impedance. Most popularly reported sensing structure for 3-DOF micro accelerometer are cross-beam type, which consists of a seismic mass suspended on a four small sensing beams in a cross shape. In this paper, a novel structure, which consists of a seismic mass suspended on double surrounding beams combined with four cross beams are used as the acceleration sensing structure.

Reduction of chip size and increase of sensitivity are the important targets of silicon-based sensors, since it increases the total die/wafer, and thus the productivity, and accordingly, decreases the total cost. Small, light weight accelerometers are necessary for many potable devices, such as camcorders, navigation systems, robot motion monitoring systems, and so on. It is sometime a challenge to maintain sensitivity of an accelerometer as chip size is decreased.

When the feature size of the sensor gets smaller, some technical issues become more serious and need to be carefully considered, such as the noise problem and the damping control.

In this paper, the design, modeling and simulation of new structure which has an overall chip size less than 700μm× 700μm for solid-state three degrees of freedom (3-DOF) micro accelerometers utilizing piezoresistive effect in single crystal Si are presented.

2 DESIGN OF THE ACCELEROMETER

The three dimensional (3D) model of the proposed novel structure for 3-DOF acceleration sensor is shown in Figure 1.

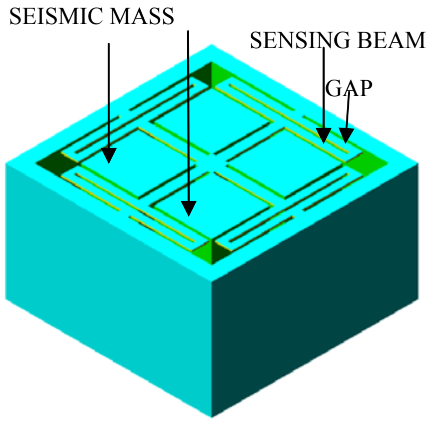

Figure 1: 3D model of the 3-DOF accelerometer.

The sensing beams are made of Si, with a seismic mass is suspended at the middles of the four surrounding beams combined with four cross beams. Si piezoresistors are formed by diffusing boron ions at the suitable places on the surface of the Si sensing beams. When an external acceleration is applied to the sensor, the seismic block will be displaced due to the inertial force. This movement of the seismic mass makes the beams deformed; as a result, the resistance of Si piezoresistors will be changed. The change of resistance will be converted to an output voltage change by a Wheatstone bridge.

2.1 Structural Analysis

In order to decide the optimal positions of the piezoresistors in the sensing beams, it is necessary to perform structural analysis. The structural analysis of the sensing chip consists of two steps. The first step deals with qualitative analysis by classical elasticity theory. The dimensions of the sensing chip were tentatively specified based on the predefined ranges of accelerations acting, e.g. ± 50g (g is the gravitational acceleration), the uniformed sensitivity condition, i.e. sensitivities to three components of acceleration are similar, and the necessary beam-width for interconnection. The Overall size of the sensing chip, includes the sensing area and the frame, which accommodates bonding pads, is 0.7×0.7×0.4 mm3, (Length ×Width ×Thickness).

Simulation using finite element method (FEM) has been performed to verify mechanical behavior of the structure as well as to optimize the design. The commercial package software ANSYS 9.0 has been used for the analysis. Figure 2 shows the FEM model of the accelerometer. The boundary condition with non-displacement of beam ends is applied.

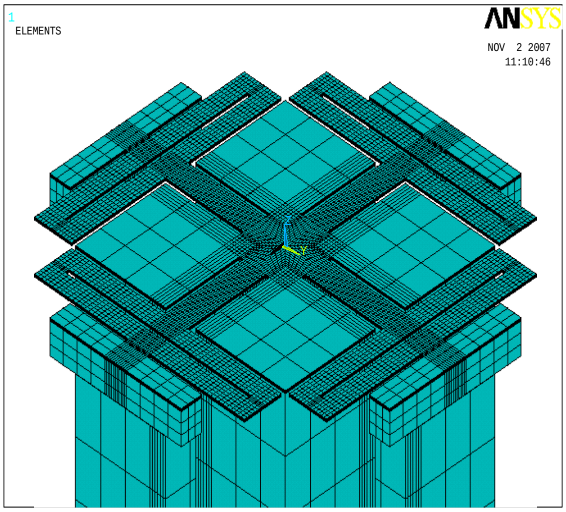

Figure 2: 3D FEM model of the accelerometer

Figures 3 to 10 show the distributions of stress components on the top surface of the beams due to application of accelerations. The FEM result shows that on the top surface of beam the stress components other than the longitudinal one can be neglected.

Modal analysis has been performed for the first three modes. Natural frequency of the first mode (vertical vibration) is f_z = 1.7 KHz, and of the second and third modes (i.e. rotational vibration around X or Y-axis) are $f_x = f_y$ = 1.2 KHz.

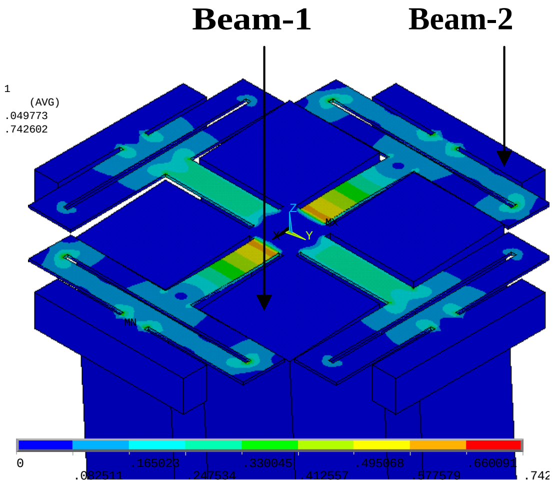

Figure 3. Graphical representation of the stress distribution on surface of X-oriented beam structure due to the application of acceleration Ax, by FEM analysis (ANSYS).

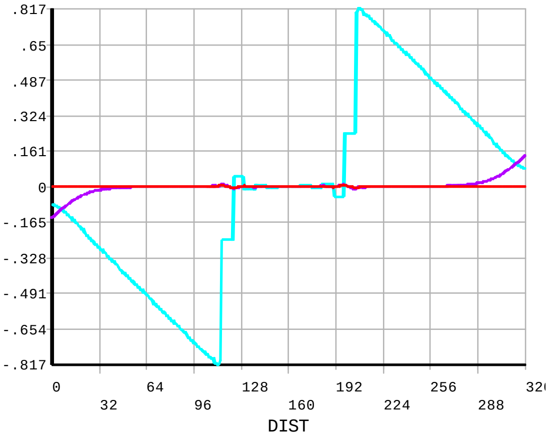

Figure 4. Stress distributions along central axis of beam-1 due to application of vertical acceleration Ax.

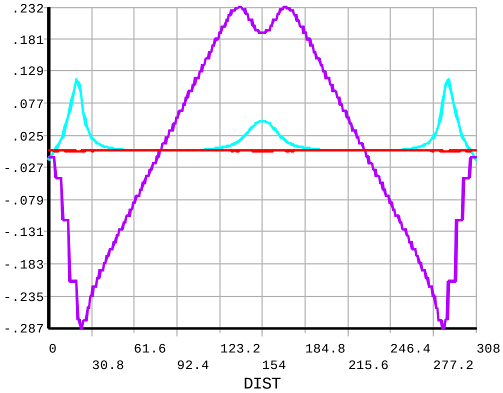

Figure 5. Stress distributions along a sensing inner side of beam-2 due to application of acceleration Ax

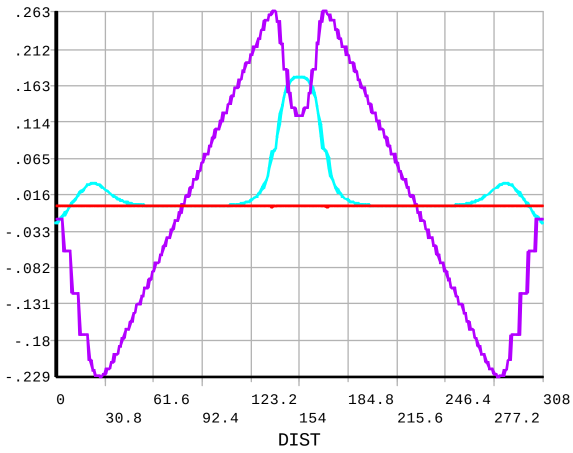

Figure 6. Stress distributions along a sensing outer side of beam-2 due to application of acceleration Ax

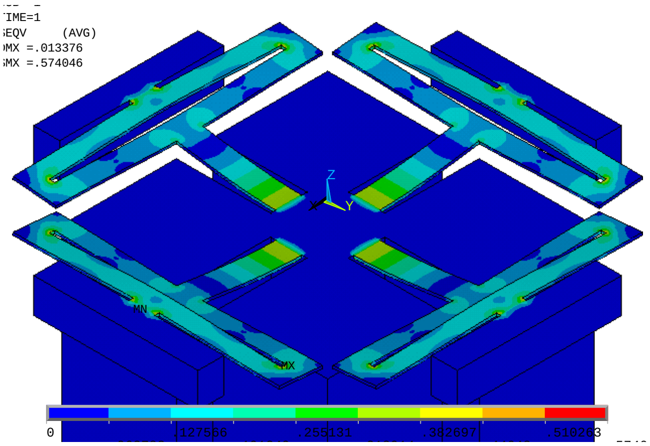

Figure 7. Graphical representation of the stress distribution on surface of beam structure due to the application of acceleration Az, by FEM analysis (ANSYS).

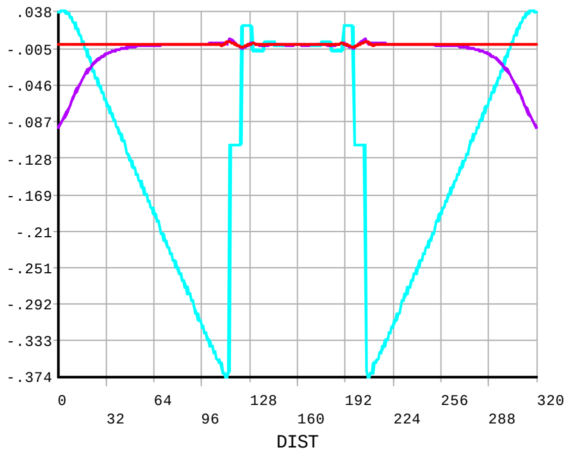

Figure 8. Stress distributions along central axis of beam-1 due to application of vertical acceleration Az.

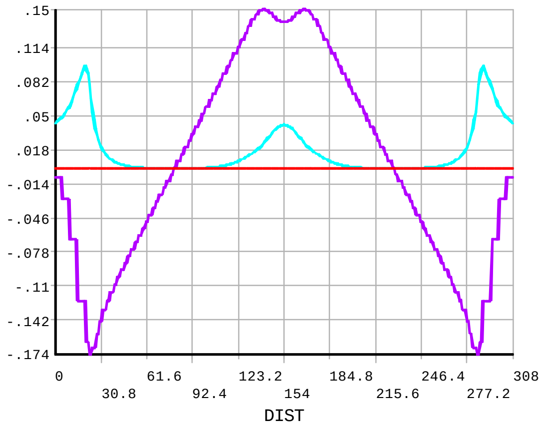

Figure 9. Stress distributions along a sensing inner side of beam-2 due to application of acceleration Az.

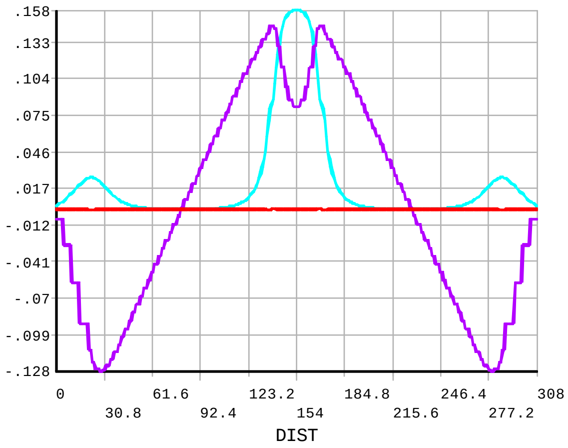

Figure 10. Stress distributions along a sensing outer side of beam-2 due to application of acceleration Ax

3 PIEZORESISTIVE EFFECT

The piezoresistive effect of conventional single-crystalline piezoresistors can be expressed as below. For a three-dimensional anisotropic crystal, the electric filed vector (ε) is related to the current vector (i) by a three-by-three resistivity tensor. Experimentally, the nine coefficients are always found to reduce to six and the tensor is symmetrical.

In matrix form this relation can be written as follows];

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_6 & \rho_5 \\ \rho_6 & \rho_2 & \rho_4 \\ \rho_5 & \rho_4 & \rho_3 \end{bmatrix} \cdot \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \qquad (1)$$

The piezoresistance effect can now be described by relating each of the six fractional resistivity changes, $\Delta\rho_i/\rho_i$ (i=1 to 6) to each of the six stress components. Mathematically this yields a matrix of 36 coefficients. By definition, the elements of this matrix are called piezoresistance coefficients, π_{ij}, (i,j=1 to 6), expressed in Pa^{-1}. In this research, two-terminal piezoresistors are formed by masked-diffusion method, and lie on very thin surface layer. Therefore, only two piezoresistance coefficients, i.e. π_{11} and π_{12} are important [2]. π_{11} corresponding to the case the stress parallels with the direction of electric field and current density, thus it is called the longitudinal piezoresistance coefficient, denoted by π_l. Similarly, π_{12} relating to the case the applied stress is perpendicular to the electrical field and current density, hence it is called transverse piezoresistance coefficient, π_t. These two coefficients can be expressed through 3 fundamental piezoresistance coefficients π_{11}, π_{12}, π_{44}, and directional cosines by:

$$\pi_l = \pi_{11} + 2(\pi_{44} + \pi_{12} - \pi_{11})(l_1^2 m_1^2 + l_1^2 n_1^2 + m_1^2 n_1^2) \tag{2}$$

$$\pi_t = \pi_{12} - (\pi_{44} + \pi_{12} - \pi_{11})(l_1^2 l_1^2 + m_1^2 m_2^2 + n_1^2 n_2^2) \tag{3}$$

where l_i, m_i, n_i, ($i = 1, 2, 3$) are directional cosines.
In directions <110> and $<1\bar{1}0>$, these coefficients can be expressed as:

$$1/2\left(\pi_{11} + \pi_{12} + \pi_{44}\right) \tag{4}$$

$$1/2\left(\pi_{11} + \pi_{12} - \pi_{44}\right) \tag{5}$$

(π_{11}=6.6x10^{-11}Pa^{-1} , π_{12}=6.6x10^{-11}Pa^{-1}, π_{44}=6.6x10^{-11}Pa^{-1})

Based on the theory and equation above, the resistance change can be calculated as a function of the beam stress. The mechanical stresses are constant over the resistors; the total resistance changed is given by:

$$\frac{\Delta R}{R} = \sigma_l \pi_l + \sigma_t \pi_t \tag{6}$$

It is noted that the above equation are only valid for uniform stress fields or if the resistor dimensions are small compared to the beam size.

4 PIEZORESISTORS ARRANGEMENT

Based on the stress distribution in the crossbeam derived from FEM analysis, piezoresistors were placed to eliminate the cross-axis sensitivities, and to maximize the sensitivities to various components of linear acceleration and angular acceleration [2]. Twelve p-type conventional piezoresistors, are diffused along the central-longitudinal axes on the upper surface of n-type silicon crossbeam. The in-plane principal axes of the piezoresistors are aligned with the crystal directions $<110>$ and $<1\bar{1}0>$ of silicon (001) plane. All conventional piezoresistors are designed to be identical as shown in Figure 11.

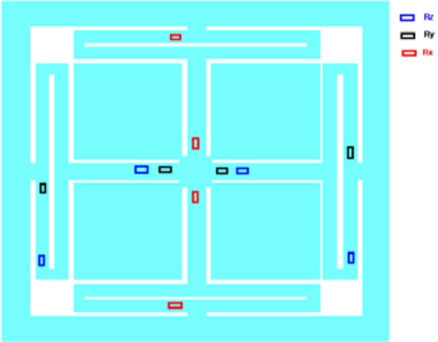

Figure 11. The arrangement of twenty piezoresistors on beam structure of the accelerometer.

	Rz1	Rz2	Rz3	Rz4	Ry1	Ry2	Ry3	Ry4	Rx1	Rx2	Rx3	Rx4
Az	+	−	+	−	−	−	−	−	−	−	−	−
Ay	−	0	+	0	−	+	−	+	0	+	+	0
Ax	−	−	+	+	0	+	+	0	−	+	−	+

Table 1 summarizes the increase (+), decrease (-), or invariable (0) in resistance of piezoresistors due to application of accelerations Ax, Ay, and Az. To detect the accelerations, piezoresistors are connected to form Wheatstone full bridges. The Wheatstone bridges to measure the accelerations Ax and Ay are similar and denoted by Ax-bridge and Ay-bridge, respectively. Similarly, for vertical acceleration Az, we have Az-bridge. The change in resistance of piezoresistors is converted to output voltage by these bridges.

4.1 Sensitivity Estimation

The sensitivity of the accelerometer can be defined as the ratio between the output voltage and the applied acceleration. With the notices that the piezoresistors of one bridge are designed to be identical, and that the transverse piezoresistive effect is very small in comparison with the longitudinal effect, the sensitivities to each components of acceleration *Ax*, *Ay*, *Az* can be calculated, $S_{Ax} = S_{Ay} =$ 0.42mV/g, and $S_{Az} =$ 0.48 mV/g.

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REFERENCES

[1]]R.Amarsinghe, D.V.Dao, T.Toriyama, S.Sugiyama, "Design and Fabrication of Miniaturized Six-Degree of Freedom Piezoresistive Accelerometer" MEMS2005 Conference, pp. 351-354, 2005.
[2] D. V. Dao, T. Toriyam, S. Sugiyama, "Noise and Frequency Analyses of a Miniaturized 3-DOF Accelerometer Utilizing Silicon Nanowire Piezoresistors" Vienna, Austria, IEEE 2004.